Exhibit 13C

Letter from Captain Mohsen El Missiry, dated 7/27/00,
Egyptian Delegation comments on
Group Chairman's Aircraft Performance Study Addendum 1

43 pages

July 27, 2000

Mr. Gregory Phillips
National Transportation Safety Board
490 L'Enfant Plaza, S.W.
Washington, DC 20594

Dear Mr. Phillips

Please find attached herewith, the Egyptian Delegation comments to be included in the docket with reference to the "<u>Group Chairman's Aircraft Performance Study Addendum #1</u>" dated April 28, 2000.

Sincerely,

[redacted]

Captain / Mohsen El Missiry
Chief of Egyptian Investigation Committee

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July 19, 2000

Aileron Split:

- Analysis of the FDR data showed non normal behavior of the inboard ailerons, outboard ailerons and elevators at the end of the airplane dive (figures 1 to 5)

- Study for the Elevator Hinge Moment for the EgyptAir Flight 990 accident was done by Mr. O'Callahan, Performance Group Chairman, and was presented to the Egyptian Delegation on December 2, 1999. This study addresses the question of whether or not the elevator split recorded on the EgyptAir 990 FDR could have been caused by aerodynamic forces on the tail surfaces (Fig 3 shows the elevator behavior at the end of the dive).
  The study concluded that an aerodynamic cause for the split is inconsistent with the performance of the airplane and the data recorded on the FDR (Attachment 1)

- The analysis that was performed on the elevators by the Performance Group Chairman used data from Boeing that was valid to a Mach Number of 0.91. At the time of the unexplained control surface movements, the speed of the airplane was much higher than 0.91. The max operating Mach no (M_{MO}) for the Boeing 767-300 is 0.86. Therefore, the airplane was flying far out of its normal operating range. Most likely shocks had been formed on one or more of the lifting surfaces. It is possible that flow separation aft of a shock could have provided the pressure differences needed to deflect the control surfaces.

- The Egyptian Delegation believed that it is likely that whatever caused the elevators to deflect as they did also caused the aileron to deflect.

- After receiving the Performance Group Chairman report on December 2, 1999, the Egyptian Delegation asked the NTSB several times to perform the same study done on the elevator surfaces to the aileron surfaces. NTSB was not responding to the Egyptian Delegation request.

- Through one of the weekly meetings with the NTSB, NTSB announced that they are not interested in what happened at the end of the dive. Using the NTSB argument, the Egyptian Delegation mentioned that, this implies that the elevator split behavior should be ignored, as it occurred also at the end of the dive. However, the NTSB insisted not to ignore the elevator split, and to ignore the ailerons split. The NTSB also added that one of the reasons for not doing the aileron study is that the input to the ailerons from the cockpit is not known. However, the outboard aileron system, is designed so as the aileron surfaces are locked at high speed (which was the case at the end of the dive), and it is known for sure that the outboard ailerons received zero input from the cockpit during the whole event.

- All the arguments presented by the NTSB justifying their reluctance to do the ailerons split study were technically unconvincing to the Egyptian Delegation. However, NTSB announced that they will not do this study.
- On March 2, 2000 NTSB presented an answer to Egyptian Delegation requests. The answer included the NTSB view about the ailerons study request as follows: "The aileron movements before and during most of the dive are consistent with normal operation. Later in the dive, at aircraft speeds above the V_D/M_D limits of the airplanes, the left and right outboard ailerons move up symmetrically in a manner consistent with aerodynamic loading. Flight test data showing similar behavior of the ailerons during wind-up turns has been provided by Boeing. There is three-second period near the end of the DFDR where the amount of float between the right outboard ailerons differs by about 4 degrees, though the aileron float becomes symmetrical once again before the end of the data. Our specialists see little benefit to the investigation to resolve the 4-degree difference between the left and right outboard ailerons during the 3 seconds. The airplane maneuvers during the accident sequence are almost completely in the longitudinal axis and are minimally affected by the motion of the ailerons. Further, given the very high Mach number during the 3 second period in question and the likelihood of shock waves with unknown effects present on the upper surface of the wing, the 4 degrees difference between the left and right outboard ailerons over three seconds does not necessarily indicate an abnormality in the lateral control system" (Attachment 2)

- Acknowledging that the NTSB decided not to do the ailerons split study; the Egyptian Delegation decided to do it and requested the data concerning the ailerons hinge moment.

- Only on March 31, 2000, Boeing submitted the Document No D613T161 "Flight control System Data for the Boeing 767 Training Simulator" after signing an agreement between Boeing and EgyptAir for the confidential use by the Egyptian Delegation.

- Upon review of the above-mentioned document, it was noticed that the outboard aileron hinge moment data page is not correct and does not include the relevant data (the page title does not match with the page chart). In addition, another mistake was noticed regarding elevator hinge moment data. It was also noticed that this Document did not include the ailerons hinge moment data as function of the body angle

- On April 21, 2000, Boeing sent the correct outboard aileron hinge moment data page and the correction for the elevator hinge moment data.(Reference Boeing Proprietary)

- Addendum 1 to the Aircraft Performance Study was presented by the Performance Group Chairman on April 28, 2000. This addendum examines whether or not the recorded elevator split could have been caused by differential hinge moments on the left and right elevator panels (as in the report presented on December 2, 1999). The study in this addendum concluded that an aerodynamic cause for the split is inconsistent with the performance of the airplane and the data recorded on the DFDR. (Boeing Proprietary Charts)

- On May 2, 2000, Egyptian Delegation Performance Group member submitted a request to the NTSB Performance Group Chairman asking to apply the same analysis made to the elevator surfaces, on the inboard and outboard ailerons as they showed split behavior at the end of the dive similar to what was shown by the elevator (Attachment 4)

- Egyptian Delegation did not receive any answer from NTSB regarding this request

- Ailerons hinge moment data as function of the body angle was received from Boeing on May 16, 2000 (Reference Boeing Proprietary Charts)

- The Egyptian Delegation performed the study on the outboard aileron following the same approach used by the NTSB in their study of the elevator system in Addendum 1. (Egyptian Delegation Study is shown in Exhibit A)

- Using the same NTSB analysis of the elevator positions, and based on the information provided by Boeing, the Egyptian Delegation found that the NTSB method used to study the elevator surfaces asymmetrical movement, did not explain the same asymmetrical movement of the ailerons which occurred at the same timing and at the same flight conditions. The Egyptian Delegation concluded that, it is likely that whatever caused the elevators to deflect as they did also caused the aileron to deflect.

- As mentioned above, the analysis that was performed on the elevators by the Performance Group Chairman used data from Boeing that was valid to a Mach Number of 0.91. Most likely shocks had been formed on one or more of the lifting surfaces. It is possible that flow separation aft of a shock could have provided the pressure differences needed to deflect the control surfaces. However, experimental data to confirm or deny this possibility apparently does not exist. Therefore, Egyptian Delegation believes that it is imperative that wind tunnel tests on the stabilizer/elevator and the wing/aileron in the 0.90 to 1.05 Mach Number range be conducted to answer these questions.

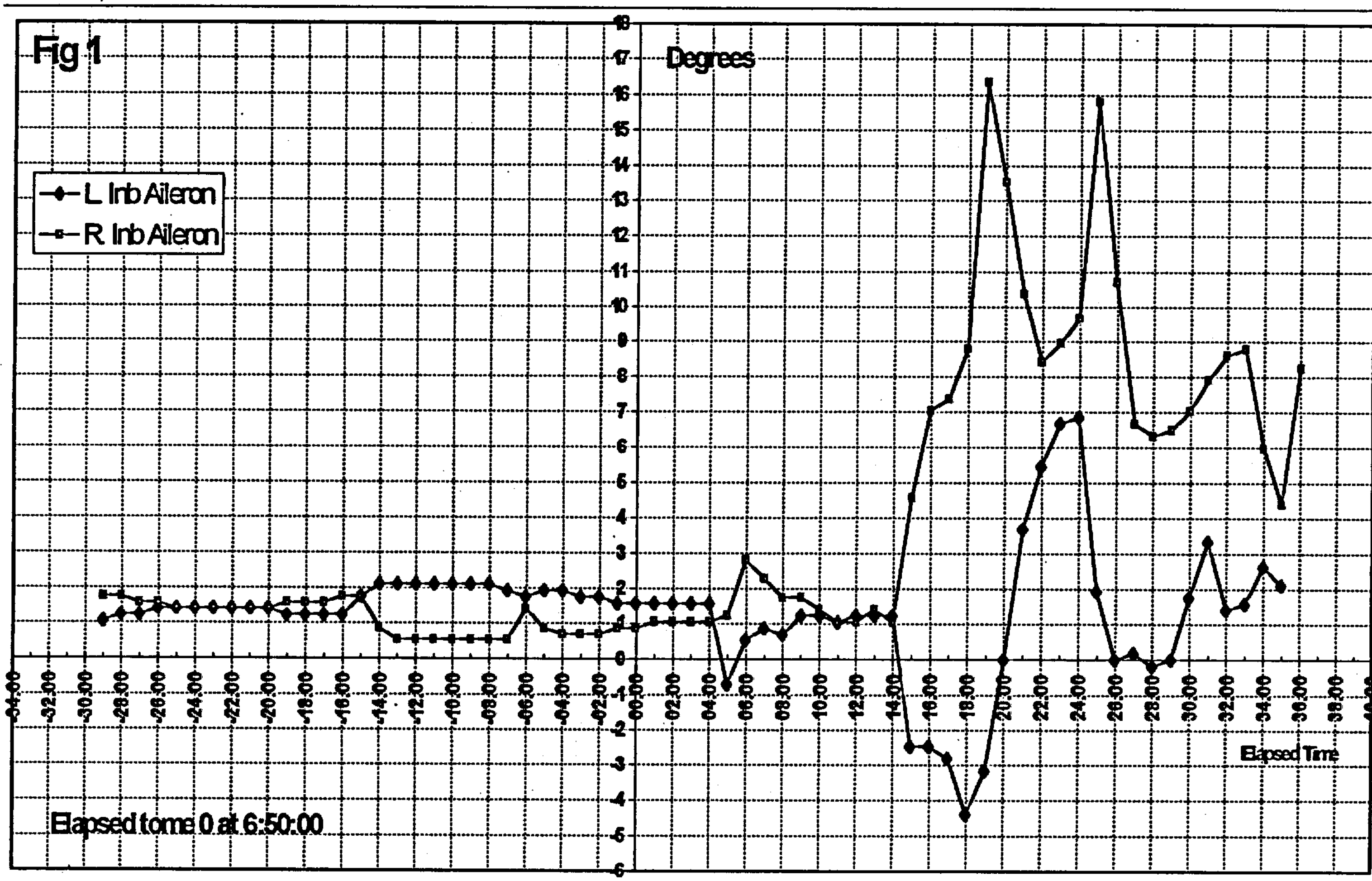

Fig 1
Degrees
L Inb Aileron
R Inb Aileron
Elapsed Time
Elapsed tome 0 at 6:50:00

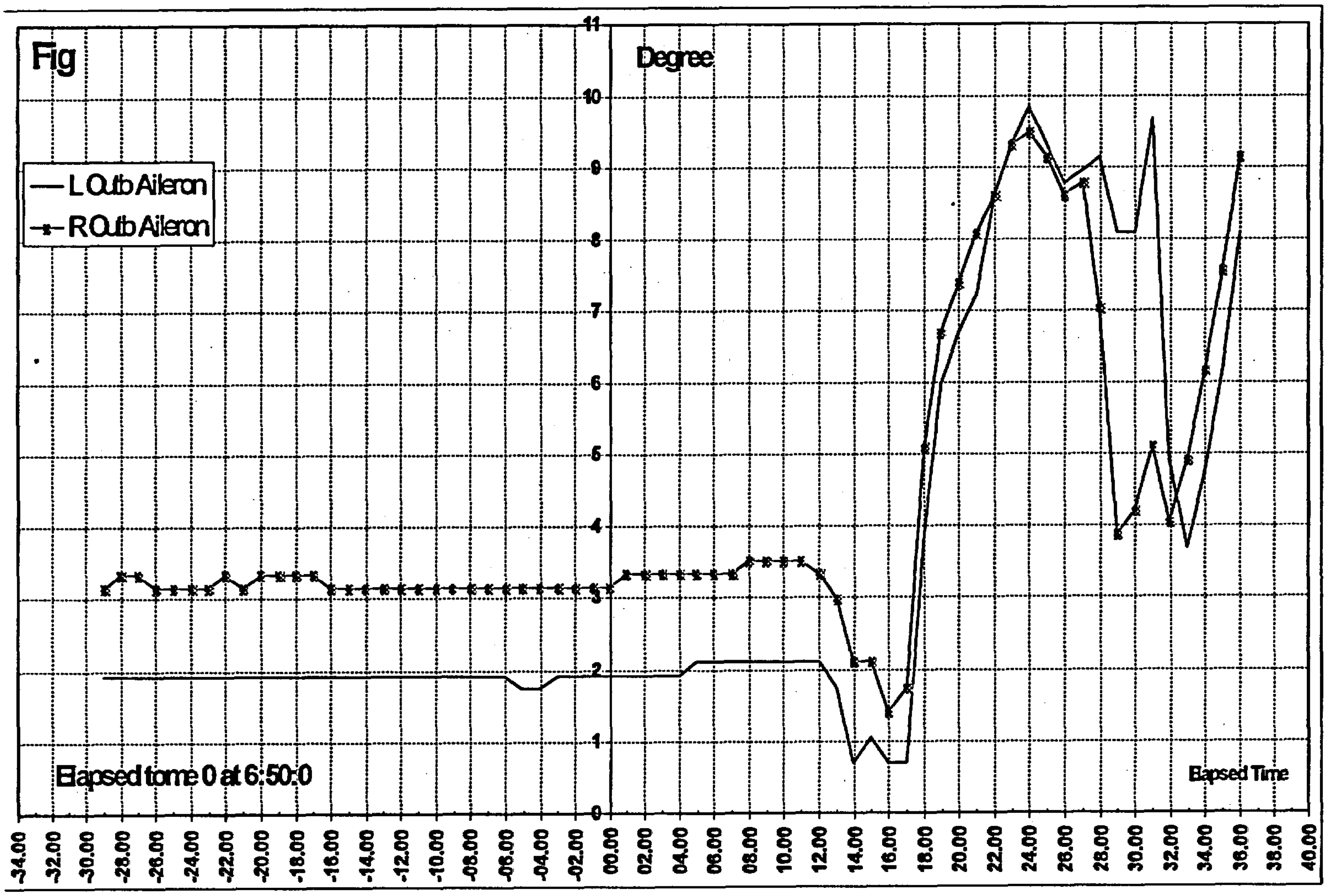

Fig
Degree
L Outb Aileron
R Outb Aileron
Elapsed tome 0 at 6:50:0
Elapsed Time

6

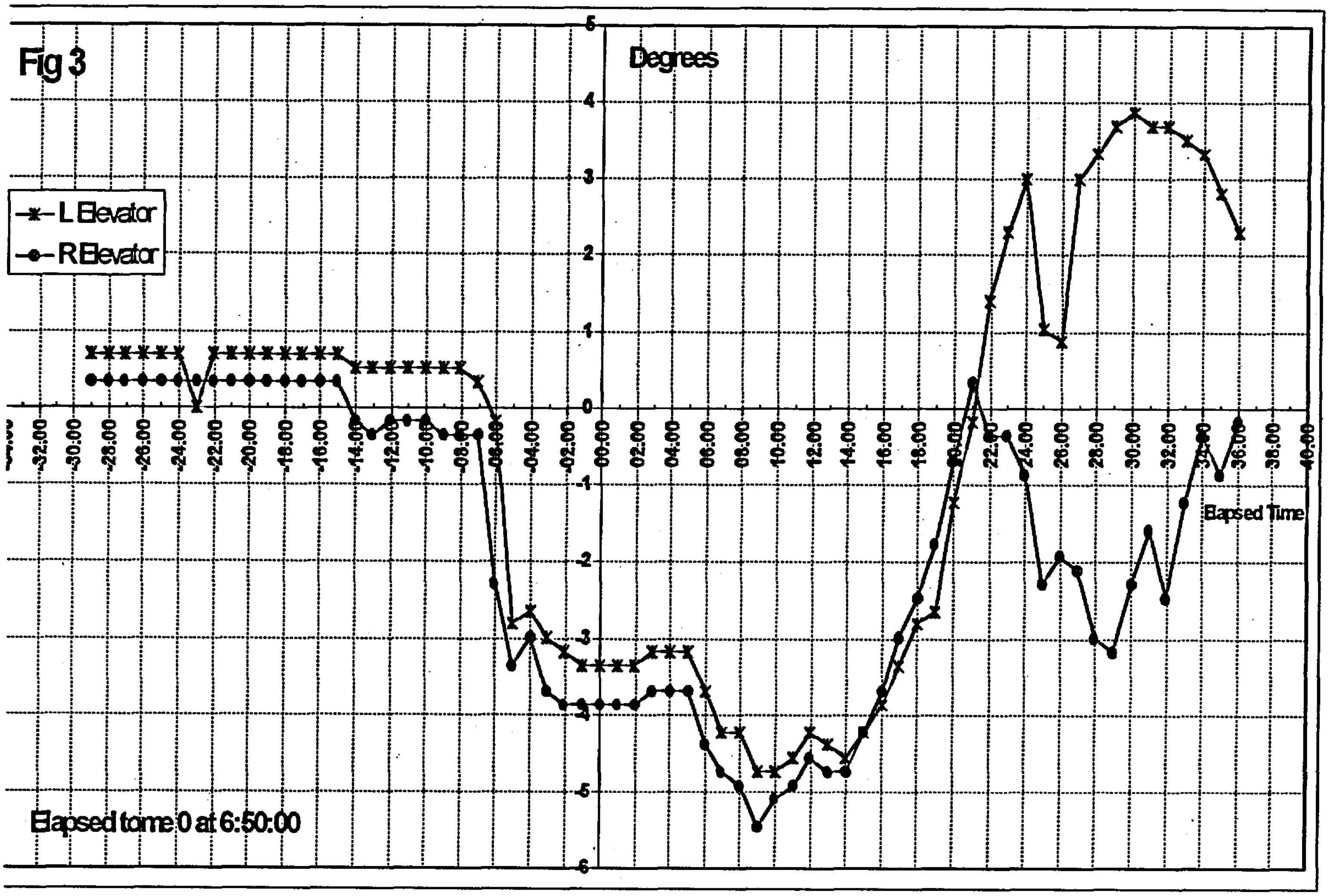

Fig 3
Degrees
L Elevator
R Elevator
Elapsed Time
Elapsed tome 0 at 6:50:00

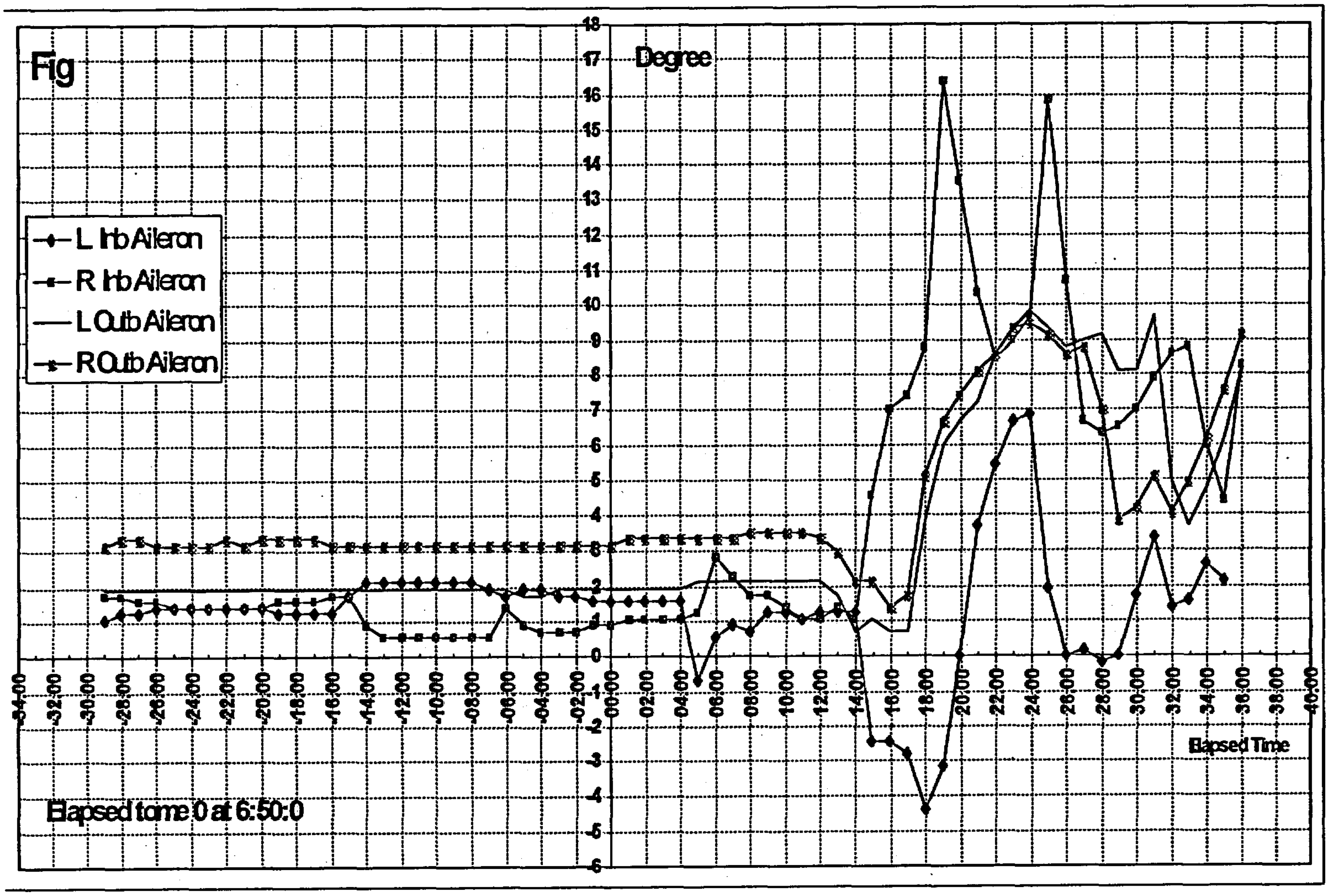
Fig
Degree
L Inb Aileron
R Inb Aileron
L Outb Aileron
R Outb Aileron
Elapsed Time
Elapsed tome 0 at 6:50:0

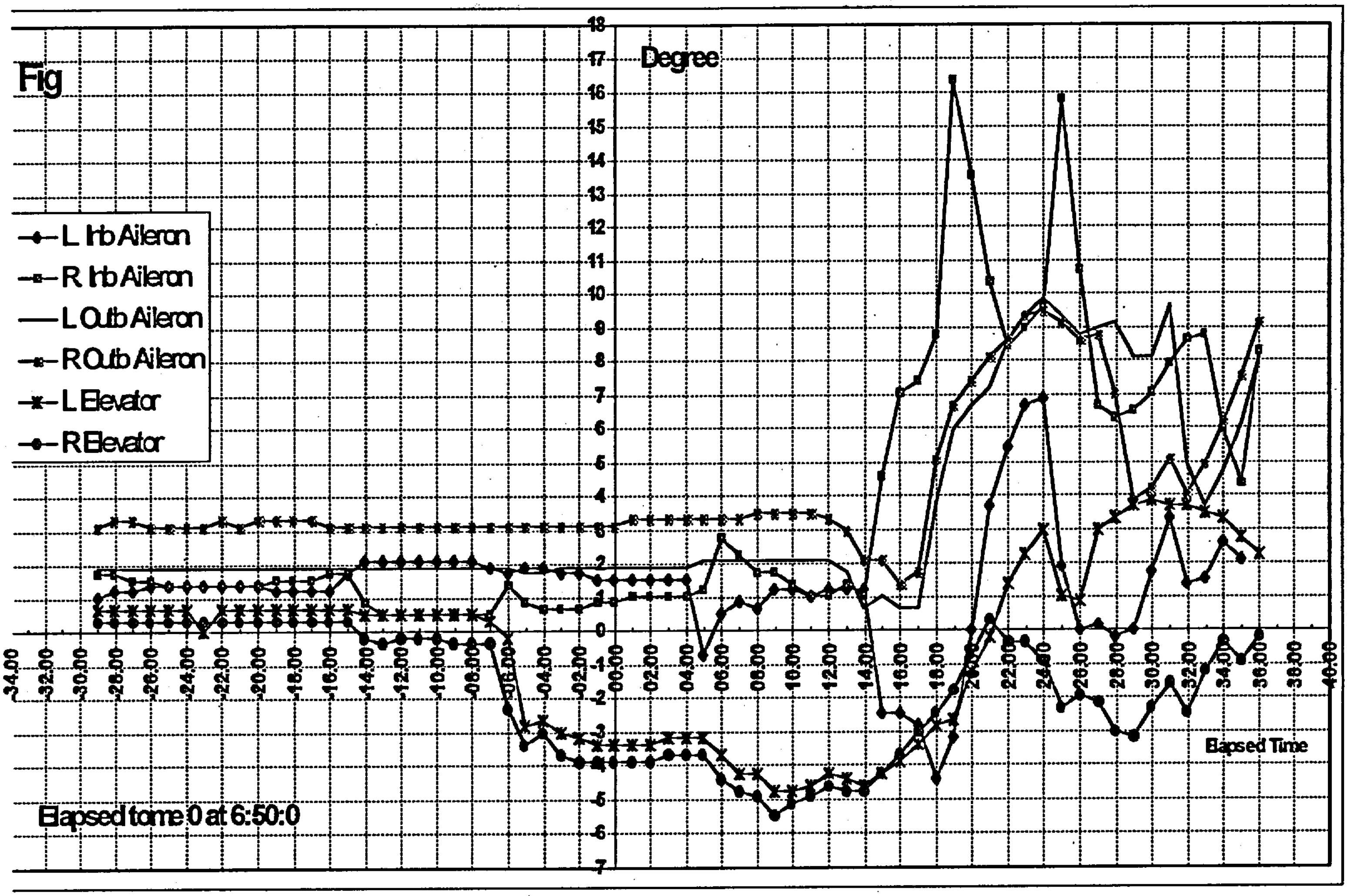
Fig
Degree
L Inb Aileron
R Inb Aileron
L Outb Aileron
R Outb Aileron
L Elevator
R Elevator
Elapsed Time
Elapsed tome 0 at 6:50:0

9/19

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EXHIBIT A

OUTBOARD AILERONS ASSYMETRIC OPERATION ANALYSIS

SUMMARY

The DFDR data indicate a split, or asymmetry, in the left and right outboard ailerons panels almost between 6:50:27.98 and 6:50:31.98 UTC. This report examines whether or not the recorded outboard aileron split could have been caused by differential hinge moments on the left and right aileron panels. The results of these calculations indicate that an aerodynamic cause for the split is inconsistent with the performance of the airplane and the data recorded on the DFDR.

REFERENCES:

- Flight Control System Data for the 767 Training Simulator
- The inboard and outboard aileron hinge moment coefficients measured on a full 767-200 model mounted in the Boeing Transonic Wind Tunnel (BTWT)

DETAILS OF THE ANALYSIS

Hinge Moments Required to Produce Outboard Aileron Split:

This section addresses the question of whether or not the aileron split recorded on the EgyptAir 990 DFDR could have been caused by aerodynamic forces on the wing surfaces.

The flight condition chosen for this study is as follows:

Radar Time: 01:50:30.98 EST
Altitude: 17152 ft.
Mach Number: 0.93 (derived from CAS and press alt. Shown in FDR data)
True Airspeed: 585 kts.
Dynamic Pressure: 662.9 lb/sq ft
Left Outboard Aileron: -9.67 degree Trailing Edge up (TEU)
Right Outboard Aileron: -5.1 degree Trailing Edge Up (TEU)

At high speeds and high altitudes, the two outboard ailerons are locked in the neutral position. (lockout mechanisms receive the locking signals from the Stabilizer and Aileron lockout Modules-SAMS). Therefore, the outboard ailerons do not receive any command from the aileron wheels at this flight condition.

With this condition, the airloads on the right outboard aileron must drive the aileron in the trailing edge up direction against the hydraulics to about 5 deg, and those on the left outboard aileron must drive the surface in the trailing edge up direction against the hydraulics to about 9 deg. The airloads that tend to rotate the ailerons about their hinges are expressed in terms of the aileron hinge moment coefficients, defined as

$$C_H = \text{Hinge Moment} / (q*S*c)$$

where
q = dynamic pressure.
S = aileron reference area.
c = aileron chord.

Documents provided by Boeing describe the C_H as a function of wing angle of attack, aileron deflection, Mach number, and flap setting. The wing angle of attack is a function of the airplane body angle of attack. According to Boeing verbal information:

$$\alpha_{waoa} = \alpha_{baoa} + 0.98 \text{ deg}$$

where,
α_{waoa} = wing angle of attack

α_{waoa} = body angle of attack

The Boeing documents enable one to calculate the amount of hinge moment that can be balanced by the forces provided by the hydraulic actuators. In the problem under consideration, the aileron deflection, Mach number, dynamic pressure, and flap setting are defined by the flight condition. If there is asymmetric flow around the left and right ailerons, then the C_H of the left and right ailerons may be different, resulting in differential hinge moments and differing surface positions. The table below lists the wing angles of attack required on the left and right wing surfaces in order to overcome the hydraulic actuator, and drive the ailerons to the split positions recorded by the DFDR at 01:50:30.98

# of Hydraulic systems Operating	α_W on left wing required to drive L. outb. aileron -9.67 deg (degree)	α_W on right wing required to drive R. outb. aileron -5.1 deg (degree)	$\Delta\alpha_W = (\alpha_{WL} - \alpha_{WR})$ (degree)
0	4.18	1.19	2.98
1	13.46	6.09	7.37
1.2	15.32	7.07	8.25
2	22.75	10.99	11.76
2.4	26.46	12.95	13.51

Linearized equations at Mach 0.91 (the highest Mach number for which 767 C_H data are available) were used to derive the numbers shown in the table.

The investigation has revealed that because the engine N2 values remained above 40% during the period for which DFDR data is available, no hydraulic power would have been lost in the time between when the engines were shut down and the DFDR ended.

The two possibilities which can generate such asymmetric flow about the left and right wings are:
(1) a roll rate,
(2) a sideslip angle.

(1) Effect of roll rate:

The half-span of the wing is 77.5 ft.

The following table shows the rate of change of roll required to generate the difference in wing angle of attack

$\Delta\alpha_W$	ω in radians/sec	ω in degrees/sec
0	0	0
1	-0.07	-3.77
2	-0.13	-7.54
3	-0.2	-11.31
4	-0.26	-15.08
5	-0.33	-18.86
6	-0.4	-22.64
7	-0.46	-26.42
8	-0.53	-30.2
9	-0.59	-33.99
10	-0.66	-37.79

The table shows that, to generate an 5 deg change in the angle of attack at both sides, requires a roll rate of about 18 degree/second, and to generate an 10 deg change in the angle of attack at both sides, requires a roll rate of about 38 degree/second.
At the flight condition in question the roll rate is approximately 2 degrees/second.

(2) Effect of side slip:

The dihedral angle of the wing is 6 degrees. This angle will cause one wing to be at a different angle of attack than the other while in a sideslip.

Side slip angle β necessary to produce α_W
M=0.91

α_W	Side Slip Angle β radians	Side Slip Angle β degrees
0	0	0
1	0.17	9.48
2	0.32	18.47
3	0.46	26.63
4	0.59	33.78
5	0.7	39.93
6	0.79	45.16
7	0.87	49.59
8	0.93	53.36
9	0.99	56.58
10	1.04	59.34
11	1.08	61.73
12	1.11	63.81

The above table shows that, to change the wing angle of attack by 5 degrees (difference of 10 between the wings) requires a sideslip angle of about 40 degree. Such a sideslip angle is inconsistent with the lateral load factor, aileron angles, and rudder angles recorded on the DFDR, and at the flight condition in question is probably beyond the aerodynamic and structural capability of the airplane.

The roll rates and sideslip angles required to generate the necessary asymmetric angles of attack on the left and right wings are inconsistent with the performance capabilities of the airplane and with the data recorded on the DFDR.

CONCLUSION:

Using the same NTSB analysis of the elevator positions, and based on the information provided by Boeing, the study shows that the NTSB method used to study the elevator surfaces asymmetrical movement, did not explain the same asymmetrical movement of the ailerons which occurred at the same timing and at the same flight conditions. It is likely that whatever caused the elevators to deflect as they did also caused the aileron to deflect.

The analyses that was performed on the elevators and that is performed on the ailerons used data from Boeing that was valid to a Mach Number of 0.91. At the time of the unexplained control surface positions, the speed of the airplane was much higher than 0.91. Most likely shocks had been formed on one or more of the lifting surfaces. It is possible that flow separation aft of a shock could have provided the pressure differences needed to deflect the control; however, experimental data to confirm or deny this possibility apparently does not exist.

Recommendation:

It is imperative that wind tunnel tests on the stabilizer/elevator and the wing/aileron in the 0.90 to 1.05 Mach Number range be conducted to answer the above questions.

Enclosure: Outboard Ailerons Assymetric Operation Mathematical Analysis

OUTBOARD AILERONS ASSYMETRIC OPERATION MATHEMATICAL ANALYSIS

$$C_{h\,\delta a} = Hm_{\delta a} \;/\; (q*S*c) \tag{1}$$

Where

$C_{h\,\delta a}$ = Outboard Aileron Hinge Moment Coefficient
$Hm_{\delta a}$ = Hinge Moment at the outboard aileron hinge
q = dynamic pressure.
S = aileron reference area.
C = aileron chord.

$$C_{h\,\delta a} = f(\alpha_W, \delta_a, M)$$

Where

α_W angle off attack of speed vector w.r.t. wing surface
δ_a outboard aileron deflection
M Mach Number

$$C_{h\,\delta a} = C_{h\,\delta a\,0}\{M=.91, \alpha_W=0, \delta_a=0\} + (\partial C_{h\,\delta a} / \partial \alpha_W)\, \alpha_W + (\partial C_{h\,\delta a} / \partial \delta_a)\, \delta_a + (\partial C_{h\,\delta a} / \partial M)\, \Delta M \tag{2}$$

$$\delta_a = \delta_{a\,com} - P_L / K_S \tag{3}$$

$$P_L = (K_L\, C_{h\,\delta E}\, q) / (n\, L_{EMA}) \tag{4}$$

$$K_L = S\,C / A_P \tag{5}$$

Where:

δ_a = outboard aileron deflection
$\delta_{a\,com}$ = commanded outboard aileron deflection
P_L = Load Press.
K_S = PCA Stiffness
K_L = PCA load factor
q = Dynamic press. of the undisturbed stream
n = Number of effective Power Control Actuators
L_{EMA} = Length of the Effective moment arm
S = Reference area
C = Reference Chord
A_P = PCA Piston Area

The outboard ailerons are designed to be locked at high speeds, therefore
$\delta_{a\,com} = 0$

$$\delta_a = -P_L / K_S \tag{7}$$

$$\delta_a = -(K_L C_{h\delta a}\, q) / (K_S\, n\, L_{EMA})$$

$$C_{h\delta a} = -(\delta_a K_S\, n\, L_{EMA})/(K_L\, q) \tag{8}$$

From equations (2), (8):

$$-(\delta_a K_S n L_{EMA})/(K_L\, q) = C_{h\delta a0}\{M{=}.91, \alpha_W{=}0, \delta_a{=}0\} + (\partial C_{h\delta a} / \partial \alpha_W)\, \alpha_W + (\partial C_{h\delta a} / \delta_a)\, \delta_a$$

$$\alpha_W = (1/(\partial C_{h\delta a} / \partial \alpha_W))\{-\delta_a [(K_S n L_{EMA})/(K_L\, q) + (\partial C_{h\delta a} / \partial \delta_a)] - C_{h\delta a0}\{M{=}.91, \alpha_W{=}0, \delta_a{=}0\} \tag{9}$$

(ignoring the $(\partial C_{h\delta a} / \partial M)\, \Delta M$ term)

Reference to the "Flight Control System Data for the 767 Training Simulator" Document:

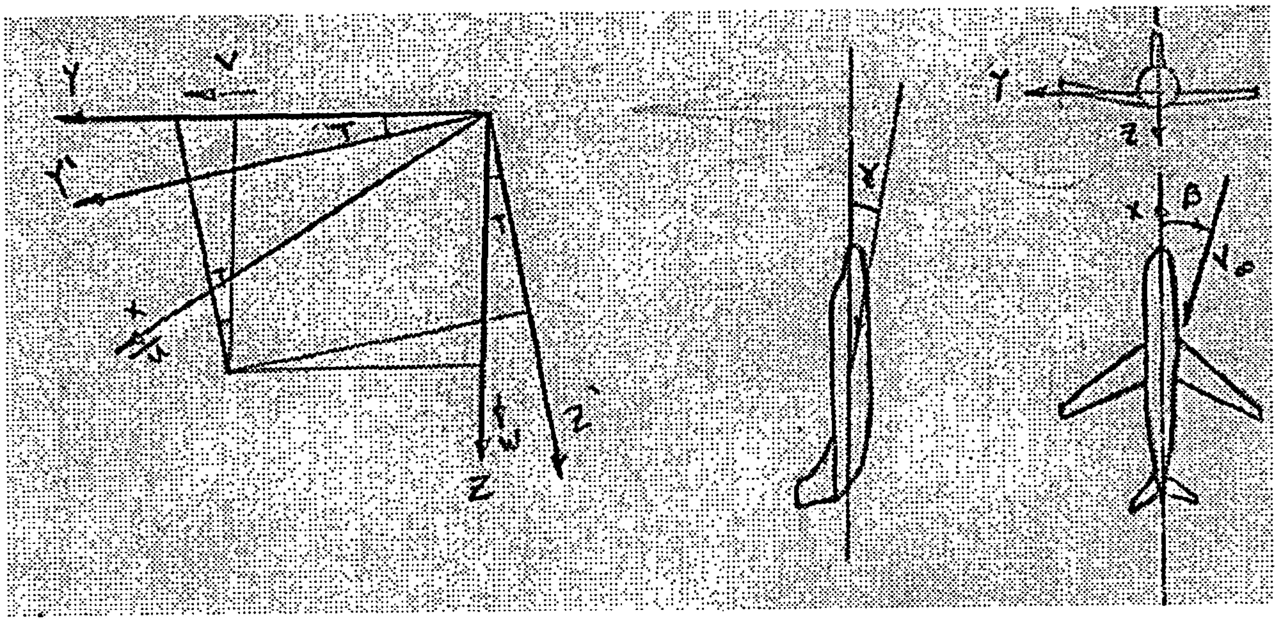
From Figure 4.6-2, Outboard Aileron PCA Model
K_S = 1235 PSI/deg
K_L = 30.64 ft^3/in^2

From Figure 4.7-2 Outboard Aileron Actuator Moment Arm
L_{EMA} = 0.259 ft

At 6:50:30.98 UTC at which the outboard aileron split occurred
M = 0.9303 (based on FDR CAS and Press Altitude)
Press Altitude = 17152 ft
TAS = 584.99 Kt
q = 662.9 Pound/ ft^2
$\delta_{a\,L.H}$ = 9.67 degrees (TEU)
$\delta_{a\,R.H}$ = 5.1 degrees (TEU)

Outboard Aileron Hinge Moments values are extracted from "The inboard and outboard aileron hinge moment coefficients measured on a full 767-200 model mounted in the Boeing Transonic Wind Tunnel (BTWT)" Document, sheet 1-6

Side Slip Effect:



x,y,z are the longitudinal, lateral and vertical axes respectively

β = Sideslip Angle

$x` = x$
$y` = y \cos\tau + z \sin\tau$
$z` = -y \sin\tau + z \cos\tau$

where
τ = Dihedral angle

$$\begin{matrix} x` \\ y` \\ z` \end{matrix} = \begin{matrix} 1 & 0 & 0 \\ 0 & \cos\tau & \sin\tau \\ 0 & \sin\tau & \cos\tau \end{matrix} \quad \begin{matrix} x \\ y \\ z \end{matrix}$$

$\alpha = \tan^{-1}(w/u)$
$\dot{\alpha} = \tan^{-1}(\dot{w}/\dot{u})$

$$\begin{matrix} u` \\ v` \\ w` \end{matrix} = \begin{matrix} 1 & 0 & 0 \\ 0 & \cos\tau & \sin\tau \\ 0 & -\sin\tau & \cos\tau \end{matrix} \quad \begin{matrix} u \\ v \\ w \end{matrix}$$

$u = V_\infty \cos\alpha \cos\beta$
$v = V_\infty \sin\beta$
$u = V_\infty \sin\alpha \cos\beta$

where
β = Sideslip Angle

$$\begin{bmatrix} \grave{u} \\ \grave{v} \\ \grave{w} \end{bmatrix} = V_\infty \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\tau & \sin\tau \\ 0 & -\sin\tau & \cos\tau \end{bmatrix} \begin{bmatrix} \cos\alpha\cos\beta \\ \sin\beta \\ \sin\alpha\cos\beta \end{bmatrix}$$

$$\begin{aligned} \grave{u} &= V_\infty \cos\alpha\cos\beta \\ \grave{v} &= V_\infty \cos\tau\ \sin\beta\ + V_\infty \sin\tau\ \sin\alpha\cos\beta \\ \grave{w} &= -V_\infty \sin\tau\ \sin\beta\ + V_\infty \cos\tau\ \sin\alpha\cos\beta \end{aligned}$$

$$\begin{aligned} \grave{\alpha} &= \tan^{-1}(\grave{w} / \grave{u}) \\ &= \tan^{-1}((-\sin\tau\ \sin\beta\ + \cos\tau\ \sin\alpha\cos\beta)/(\cos\alpha\cos\beta)) \end{aligned}$$

Assuming α is small

$$\begin{aligned} \grave{\alpha} &= \tan^{-1}(\sin\tau\ \sin\beta / \cos\beta) \\ &= \tan^{-1}(-\sin\tau\ \tan\beta) \end{aligned}$$

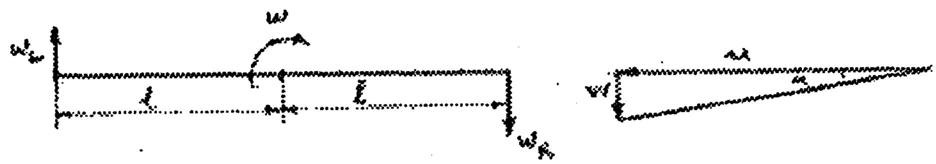
$$\begin{aligned} \tau_L &= -\tau_R \\ \grave{\alpha}_L &= \tan^{-1}(-\sin\tau_L \tan\beta) \\ \grave{\alpha}_R &= \tan^{-1}(\sin\tau_R \tan\beta) \end{aligned}$$

$$\begin{aligned} \tan\grave{\alpha}_L &= -\sin\tau_L \tan\beta \\ \tan\grave{\alpha}_R &= \sin\tau_R \tan\beta \end{aligned}$$

$$\begin{aligned} \tan\beta &= -\tan\grave{\alpha}_L / \sin\tau_L \\ \beta &= -\tan^{-1}(\tan\grave{\alpha}_L / \sin\tau_L) \end{aligned}$$

Wing dihedral angle (τ) = 6 degrees

Roll Rate Effect:



W_L $= -\omega\, l$
W_R $= \omega\, l$

Where
W_L = Vertical speed at the left wing tip
W_R = Vertical speed at the right wing tip
ω = roll angular velocity
$2l$ = Wing span
U = Forward speed

$\alpha = \tan^{-1} W/U$

$\Delta\alpha_L = \tan^{-1}(- W^* \, l/U)$ (left wing)
$\Delta\alpha_R = \tan^{-1}(W^* \, l/U)$ (right wing)

$\Delta\alpha = \Delta\alpha_L . \Delta\alpha_R = 2^* \, \Delta\alpha_L$

$\Delta\alpha_L = ½ \, \Delta\alpha$

$\tan(½ \, \Delta\alpha) = \tan \Delta\alpha_L = - \omega \, l/U$

$\omega = (-U/l) \tan(½ \, \Delta\alpha)$

$2l$ = 155 ft

U = 584.99 Kt

Attachment 1

Results of Elevator Hinge Moment Study for EgyptAir 990

Attachmet 1

December 2, 1999

These notes address the question of whether or not the elevator split recorded on the EgyptAir 990 DFDR could have been caused by aerodynamic forces on the tail surfaces. The results of the calculations described herein indicate that an aerodynamic cause for the split is inconsistent with the performance of the airplane and the data recorded on the DFDR.

The flight condition chosen for this study is as follows:

DFDR Time:	1284 s. (Based on RAPS "recovery" file)
Radar Time:	01:50:30 EST
Altitude:	17,500 ft.
Mach Number:	0.935
True Airspeed:	590 kts.
Dynamic Pressure:	655 lb/ft^2
Left Elevator:	4° Trailing Edge Up (TEU)
Right Elevator:	3° Trailing Edge Down (TED)

To evaluate the aerodynamic loads on the tail surfaces required to result in the split, an assumption must be made about where the airplane's control system is attempting to position the elevators. Note that at the flight condition under consideration the elevators are split almost an equal amount about the faired elevator position, in opposite directions. These notes therefore assume that the control system is attempting to command a 0° or faired elevator position.

With this assumption, the airloads on the right elevator must drive the elevator in the trailing edge down direction against the hydraulics, and those on the left elevator must drive the surface in the trailing edge up direction against the hydraulics. The airloads that tend to rotate the elevators about their hinges are expressed in terms of the elevator hinge moment coefficients, defined as

Ch = Hinge Moment/(q*S*c)

where q = dynamic pressure, S = elevator reference area, and c = elevator chord. Documents provided by Boeing describe the Ch as a function of tail angle of attack, elevator deflection, Mach number, and flap setting. The Boeing documents also indicate the amount of hinge moment that can be balanced by the forces provided by the hydraulic actuators. In the problem under consideration, the elevator deflection, Mach number, dynamic pressure, and flap setting are defined by the flight condition, and so the only variable available to cause differential hinge moments on the left and right elevators is the tail angle of attack, α_H. The table below lists the angles of attack required on the left and right horizontal tail surfaces in order to overcome both the hydraulic actuators and the elevators' own tendency to return to a faired position, and drive the elevators to their split positions.

Linearized equations were used to derive the numbers shown in the table. These work well for small elevator deflections (+/- 5°) and angles of attack. However, the equations break down at larger angles of attack, because they do not account for tail stall, and can give tail angles of attack well above the stall. According to Boeing data, at low speed the tail will stall (reach its maximum lift coefficient) at angles of attack of about +/- 21°. At high speed, the stall angles are probably somewhat smaller, though wind tunnel data does not exist for these conditions.

# of Hydraulic Systems Operating	α_H on left tail required to drive elevator 4° TEU	α_H on right tail required to drive elevator 3° TED	Angle of attack difference, left - right
0	10.3°	-5.5°	15.8°
1	18.2°	-11.5°	29.7°
2	26.2°	-17.5°	43.7°
3	34.2°	-23.5°	57.7°

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The table indicates that with hydraulic power equivalent to 2 or more hydraulic systems operating, there is no angle of attack below tail stall that will move the elevators to their split positions. The investigation has revealed that because the engine N2 values remained above 40% during the period for which DFDR data is available, no hydraulic power would have been lost in the time between when the engines were shut down and the DFDR ended.

Considering the cases for which the elevator split can be obtained with tail angles of attack below stall (corresponding to 0 and 1 hydraulic systems operating), note that a considerable angle of attack difference between the left and right horizontal tails is required. It is difficult to conceive of a flight condition that can generate such asymmetric flow about the left and right horizontals, but two possibilities are (1) a roll rate, and (2) a sideslip angle.

The half-span of the tail is approximately 30 ft. At 590 kts., to generate a 5° angle of attack change at the tip of one horizontal (i.e., a 10° difference between left and right horizontal tips) requires a roll rate of 250 degrees/second. At the flight condition in question the roll rate is approximately 2 degrees/second.

The dihedral angle of the tail is 7°. This angle will cause one horizontal to be at a different angle of attack than the other while in a sideslip. However, to change the tail angle of attack by 5° (difference of 10° between the tails) requires a sideslip angle of 35°. Such a sideslip angle is inconsistent with the lateral load factor, aileron angles, and rudder angles recorded on the DFDR, and at the flight condition in question is probably beyond the aerodynamic and structural capability of the airplane.

The calculations outlined in these notes indicate that with little loss of hydraulic power, there is no angle of attack on the tails below the tail stall which can generate the elevator split recorded on the EgyptAir DFDR. Furthermore, even at reduced hydraulic power where angles of attack below tail stall can cause the split, the roll rates and sideslip angles required to generate the necessary asymmetric angles of attack on the left and right horizontal tails are inconsistent with the performance capabilities of the airplane and with the data recorded on the DFDR.

[redacted]

John O'Callaghan
Airplane Performance Group Chairman – EgyptAir Flight 990 Investigation
NTSB Office of Research and Engineering – Vehicle Performance Division

Attachment 2

March 2, 2000

Captain Moshen El Missiry
Chief of Egyptian Investigation Committee
Egypt Civil Aviation Authority

Dear Captain El Missiry,

Thank you for your letter of February 7, 2000, identifying operational and aircraft issues that the Egyptian delegation believes need further consideration in the investigation of the EgyptAir Flight 990 accident.

I have asked each of the responsible group chairmen for the disciplines noted to respond to your requests. The following comments represent their response. Your request from the February 7, 2000, letter appears in bulleted bold type. The Safety Board's response follows.

Aircraft Systems/Structures Groups

- **Examine the elevator actuators by assembling (fracture matching and part form) of all of the recovered elevator and matching stabilizer structures (including linkages) in a two-dimensional layout.**

  All recovered elevator actuators and stabilizer structure were examined by Safety Board, Boeing, and EgyptAir staff in the hangar at Quonset Point. Additional metallurgical examinations of all recovered components of the longitudinal control system (including the stabilizer jackscrew) were accomplished on February 25-26, 2000, by Safety Board and Boeing metallurgists assisted by an EgyptAir metallurgist consultant. These examinations indicated no evidence of pre-impact failure.

  Portions of the horizontal stabilizer jackscrew were examined in the Safety Board metallurgy lab. This examination indicated that all failures were typical of overstress.

  Examinations of newly recovered wreckage will be conducted after recovery from the accident site.

- **Examine the elevator actuators, with detailed photographs of the exterior followed by disassembly to examine the internal portions (servo slides and matching internal housings) for evidence of internal jamming.**

  Additional examination, photography and disassembly of the elevator actuators will be conducted at Boeing facilities in Seattle, Washington. The actuators have

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been shipped to Seattle and are being held in the Safety Board's offices in Seattle for the examinations. The date of the examinations has not been set and is pending the resolution of the labor action at Boeing.

- **Locate and examine available mechanical linkages for evidence of external jamming, noting the fracture positions and associated deformations. All fractures in the linkages should be analyzed for evidence of pre-existing condition.**

  The recovered elevator actuators and stabilizer structure were examined in the hangar by Safety Board, Boeing, and EgyptAir staff. Additional metallurgical examinations of the mechanical linkages for evidence of external jamming was accomplished on February 25-26, 2000, by Safety Board metallurgists and an EgyptAir consultant. These examinations indicated no evidence of pre-impact failure.

  Examinations of newly recovered wreckage will be conducted after recovery from the accident site.

- **Review wreckage diagrams to assess what parts of the elevator control system and related control surfaces and linkages have been recovered and reach agreement on any further efforts to recover additional related parts.**

  The wreckage diagram has been reviewed. Additional aircraft wreckage recovery is tentatively planned for late March 2000.

- **Examination of salvaged components by systems and metallurgical experts.**

  The salvaged components were examined in the hangar by Safety Board, Boeing, and EgyptAir staff. Additional metallurgical examinations of the elevators, elevator linkages, and empennage structure were accomplished on February 25-26, 2000, by Safety Board and Boeing metallurgists assisted by an EgyptAir metallurgist consultant. These examinations indicated no evidence of pre-impact failure.

  Examinations of newly recovered wreckage will be conducted after recovery from the accident site.

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- **Obtain from Boeing and FAA all data pertaining to problems associated with the elevator system hardware, such as improper functioning of the actuator, possible cracking or failure of the linkages or other similar problems on related aircraft such as the B757**

  Service difficulty reports (SDR), airworthiness directives (AD), and Boeing maintenance information have been requested for the B767. A review of potential failure modes and effects has been conducted with the EgyptAir staff. Preliminary reviews of the SDRs, ADs, and maintenance information provide no indication of cracking or failure of the elevator system hardware in the Boeing 767. Information for the Boeing 757 has been requested, and will be reviewed when it arrives.

- **Obtain from Boeing or other appropriate source the following:**

  Engineering drawings for control system components, such as the internal design of the PCU.

  The Safety Board has engineering drawings of system components. We have not obtained the detailed drawings of the PCU. Detailed PCU drawings will be used during the PCU examinations at Boeing. The Safety Board will not provide copies of proprietary documents outside of the Safety Board staff.

  Maintenance history of B767 fleet regarding flight control system problems, including Boeing MRR data, ATA data base, etc.

  Service difficulty reports, airworthiness directives, and Boeing maintenance information have been requested for the Boeing 767.

  Maintenance history of airplanes having similar systems and component design, including the full report of the B747 elevator incident.

  The data for the Boeing 767 will be reviewed prior to determining if maintenance information for other airplanes is needed. The report on the British Airways Boeing 747 elevator incident is in the Safety Board's public docket for the USAir flight 427 accident investigation. A copy will be provided to the Egyptian delegation.

  Charts relating elevator Q feel pressure with aircraft speed (Mach number)

  The Safety Board has requested this information from Boeing.

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Charts relating EPR with normalized engine parameters at EPR values less than .9 (0.6 to 0.9)

The Safety Board has requested this information from Boeing and Pratt and Whitney (P&W).

To confirm the validity of the data, P&W has indicated that they need the DFDR data for altitude and Mach number when those EPR values were recorded. At the time the 0.6 to 0.9 EPR condition occurred, the airplane was beyond the envelope for existing data. The EgyptAir flight 990 airplane provides the only known data. Although P&W has indicated that they could generate some data to respond to these questions, they have serious concerns about the quality of that data and any generated data would not be validated.

Data regarding V-n values at which the airplane loses structural integrity.

This information is not necessary to the investigation as the radar and FDR data do not indicate a loss of structural integrity during the initial dive, through the end of the FDR data, and the subsequent climb.

Copy of Boeing Report B-H200-16855-ASI, including hinge moment information in all aircraft axes.

The Safety Board has requested this information from Boeing.

Detailed drawings or DFDR transducer installations

The Safety Board has drawings of the DFDR transducer installations.

AIRCRAFT PERFORMANCE

- **Tests and simulations to correlate the flight profile and airplane attitude parameter (based upon DFDR/ATC radar data) with DFDR control surface position, engine power and airspeed parameters. The simulation must examine aircraft performance, e.g. pitching and rolling moments associated with split elevator condition. The deflection of the inboard and outboard aileron movements before and during the dive must also be analyzed.**

Numerous simulations correlating the flight profile and aircraft motion with DFDR control surface positions and engine parameters have already been completed at Boeing and reviewed by all parties to the investigation. These simulations are being continuously refined as investigators work with Boeing engineers to improve the modeling of the longitudinal control system to account for the specific events recorded in the DFDR data, including the split elevator

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condition. Further work in this area awaits the resolution of labor action at Boeing.

The aileron movements before and during most of the dive are consistent with normal operation. Later in the dive, at aircraft speeds above the V_D/M_D limits of the airplane, the left and right outboard ailerons move up symmetrically in a manner consistent with aerodynamic loading. Flight test data showing similar behavior of the ailerons during wind-up turns has been provided by Boeing. There is a three second period near the end of the DFDR where the amount of float between the left and right outboard ailerons differs by about 4 degrees, though the aileron float becomes symmetrical once again before the end of the data.

Our specialists see little benefit to the investigation to resolve the 4 degree difference between the left and right outboard ailerons during the 3 seconds. The airplane maneuvers during the accident sequence are almost completely in the longitudinal axis and are minimally affected by the motion of the ailerons. Further, given the very high Mach number during the 3 second period in question and the likelihood of shock waves with unknown effects present on the upper surface of the wing, the 4 degree difference between the left and right outboard ailerons over three seconds does not necessarily indicate an abnormality in the lateral control system.

- **Tests and simulations in a full flight simulator to analyze an accident scenario based on the failure of two elevator actuators on one elevator, including a consideration of failures in the actuators and/or actuators and/or failures in the linkages in the system.**

  This activity is planned and is pending resolution of the labor action at Boeing.

- **Tests and simulations to demonstrate the effect of disconnecting the input linkage from the servo valve on one of the elevator PCUs on elevator surface movement, control column feed back to determine whether such failure would be apparent during normal preflight and flight operations.**

  This activity is planned and is pending resolution of the labor action at Boeing.

- **Assess the proposed split elevator effect on aircraft performance and correlate the elevator split with the aircraft profile during and after recovery from the dive.**

  This work in progress.

- **Assess the effect of full opening of the outflow valve during flight and the time required to climb 10,100 feet.**

  This item was completed on February 11, 2000.

- **Analyze the control column forces that may have been experienced during the accident event, including the forces associated with the elevator feel spring and any asymmetry breakout components that may have been activated. In assessing the human performance aspects of force applications, control wheel roll commands and forces should be considered as well as control column push forces.**

  This activity will be accomplished as part of the simulator studies and is pending resolution of the labor action at Boeing.

- **Reexamination of the B767 elevator control system for failure modes that could cause uncommanded movement of the elevator of case a split in elevator position.**

  Accomplished by systems group.

- **Prepare an official correlation of DFDR, CVR and radar data with supporting data showing correlation methodology.**

  This work is complete. Mr. Cash gave a copy of the text to the Egyptian delegation on Monday 2/21/00. This text will appear in the airplane performance group factual report being prepared by Mr. O'Callaghan.

- **Obtain FAA certification data of the B767 flight control system, including the basis of certification, failure mode and effect analyses, (FMEA) required or conducted, design criteria for redundancy, etc.**

  This item is on hold-pending the results of simulation studies.

- **Obtain any special conditions to B767 certification by foreign authorities relating to flight control systems.**

  This item is on hold-pending the results of simulation studies.

- **Obtain from Boeing engineering data necessary to conduct or confirm elevator hinge moment analysis, including the characteristics of the elevator feel system need to analysis control column forces during the accident event.**

  Will be provided during the simulation study activities.

- **Obtain from Boeing any data or analyses pertaining to airplane performance with split elevators, including the pitch and rolling moments. (Additional tests may be required to obtain this data).**

  On hold-pending simulation studies.

<u>AIR TRAFFIC CONTROL/RADAR GROUP</u>

- **FAA Order 7400.8 and ICAO 4444.**

  FAA Orders are public documents, available from the Government Printing Office.

  ICAO document 4444, PANS-RAC – Rules of the Air and Air Traffic Services is available from ICAO.

- **Charts covering the route of MSR990 from JFK to DOVEY including Warning Areas, (Jeppesen North Atlantic Plotting Chart.)**

  The Egyptian delegation may get this information from the Jeppesen Company. The Safety Board has this information and it is available for review but it cannot be reproduced.

- **Recorded video tape for accident from ZNY and Boston Centers in two scales (R 50 NM & 200 NM)**

  Video recording of ATC information does not exist. The SATORI playback system does not reflect the actual display presented to the controller in a perfectly accurate format. The FAA Technical Center has the capability to use the original SAR (System Analysis Recording) tape to duplicate NY Center's Host processing. This process carries an extremely high cost both financially and in manpower. Preliminary estimates run over $240,000.

  It is possible to provide the "raw data" that drives the SATORI, i.e. the NTAP and DART files and, ZNY ACES files, and, however, this will not create a video presentation, it is computer message data that requires training to read. The last 15 minutes of the flight in NTAP and DART extractions can be provided at cost

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commensurate with a FOIA request. Safety Board has NTAP and DART information (along with viewing of the SATORI) sufficient for our purposes.

- **Letter of agreement between FAA and military authorities concerning special use (Warning Areas W102, W105, W106.)**

  These documents exist, and may be produced by FAA staff at NY and Boston ARTCC's. There is a manpower cost involved and were a similar request to be received through FOIA, billing for the specialist's time would be made.

- **The list of the activated warning areas during October 1999 (conditions, period of activation and the notification of releasing back to FAA)**

  These records have gone beyond the date of retention and no longer exist. The logs for October 31 were retained as part of the MSR990 investigation.

- **A description of the responsibilities of R86A**

  We are uncertain why this information would be needed for the investigation.

  The general associate position duties are spelled out in FAA Order 7110.65 and in the local facility SOP. FAA Specialist time is involved in obtaining such items. However, it appears the request refers to the R86A indicated on the ZNY transcript. This was another controller who, observing the situation, came over to help R86. There is no official reference for such an occurrence.

- **The steps that must be taken for the controller to override the XXXX in the data block and display the mode C.**

  These computer entries are not the type that appear in a simple format. Ms. Rowlett explained the process to the delegation. This technique or information is of the type which is part of personal OJT at appropriate facilities. "Overriding" the XXXX is not a required response by the controller, it is not a "checklist item" type of computer entry.

  In order to provide such information in written form, a search of the NAS software documentation (NAS MD's) would need to be done. There may be many widespread portions which apply. Such a search would be very time-consuming. Again, were this a FOIA request, many hours of Air Traffic or Automation Specialist time would be charged.

- **Multi Radar Coverage charts for New York and Boston Centers at 5000, 10000, 20000, and 30000 feet.**

  Such a chart is not needed for the investigation. In order to provide such a chart, records of baseline radar certification studies and flight check records would need to be pieced together to form a new product. It may be possible to search Airways Facilities records for such products.

- **Multi radar tracking mosaic and clutter charts and interference study for radar sites**

  The mosaic information is not required for the Safety Board's investigation.

  We have provided a chart from ZNY that indicates the preferred radar sites for each sort box. Supplemental sites could be added to this chart by specialists at ZNY. ZNY specialists used the Host/DSR to indicate the preferred/supplemental sites for the sort boxes surrounding the accident to Safety Board investigators on site. Providing a chart with geographic references would entail ZNY specialists creating a new product.

  Clutter and interference studies would be included in the previous item were it deemed necessary. Explanations from Air Force experts on clutter and interference were sufficient to satisfy Safety Board Investigators. The performance group chairman (John O'Callaghan) has incorporated the explanation in his report.

- **The configuration of the ATC System, including radar and flight data processors, radar and voice data recorders and voice communication switching system, for the relevant radar sites.**

  In order to conduct an investigation, the configuration of the ATC system must be understood. We rely on our investigators experience and knowledge to provide that understanding.

  Our ATC specialists have attempted to explain any aspect of the system that the delegation is interested in, and will continue to do so as required. There may be a commercial publication available to meet the requirements of this request. Our ATC specialist will provide the delegation and Airman's Information Manual (AIM).

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- **The printed log file for the Host/NAS system at the relevant sites.**

  The New York Host/NAS certification log has been provided to the Egyptian delegation.

- **The last flight check reports for relevant radar sites.**

  This information is not required for the Safety Board's investigation. If it is deemed appropriate to provide such information, it would require an Airways Facilities or Flight Inspection Specialist to perform a document search and reproduction.

- **The date of provisional and formal acceptance of the Host/NAS system at the relevant radar site.**

  This information is not required for the Safety Board's investigation.

- **The extracted data for all targets in ZNY Boston and Nantucket radars from 0620 to 0700 UTC on October 31, 1999.**

  This data has been provided electronically, and resides on the same CD as the DFDR data.

- **Any additional ATC data, including any military radar data from relevant sites at the time of the accident event.**

  The Safety Board has all pertinent radar data for the time of the accident.

- **A reexamination of all available radar data for primary targets that may represent other aircraft at the separation of the Flight 990 aircraft.**

  The radar data has been examined many times for other aircraft and separation. There are no additional plans to re-examine the radar data.

<u>FLIGHT DATA RECORDER GROUP</u>

- **Resolve questions concerning DFDR data of ground speed and DME frequency.**

  This item is complete. A CD has been provided to the Egyptian delegation.

- **Determine reliability of DFDR data in light of accident profile, including an analysis of the raw data and the algorithms used to convert that data to readout parameters.**

Safety Board investigators believe that the DFDR data is reliable. Further analysis of raw data and conversion algorithms is not required for the investigation.

- **Discuss and agree on official DFDR readout parameters.**

  Safety Board investigators believe the DFDR data is correct.

- **Prepare a correlation of DFDR, CVR, and radar data for the accident with data supporting the correlation methodology.**

  This work is complete. Mr. Cash gave a copy of the text to the Egyptian delegation on Monday 2/21/00. This text will appear in the airplane performance group factual report being prepared by Mr. O'Callaghan.

COCKPIT VOICE RECORDER GROUP

- **Additional analysis of the CVR is required in the following areas:**
  - **The time between when the Captain left the cockpit and the beginning of the dive.**
  - **The number of persons in the cockpit before the Captain left**
  - **Confirmation that the cockpit door was opened and remained open.**
  - **The unidentified sounds on the recording, including the sounds between the time that the Captain left the cockpit and the phrase "control it" and the sounds at 1859 (three seconds after the start of the master warning).**

  These issues are being addressed in the Mr. Cash's and Dr. Brenner's report.

  Mr. Cash's report will be available within the next 2 weeks. Dr. Brenner's draft report has been provided to the Egyptian delegation and will be finalized by the end of March.

HUMAN PERFORMANCE GROUP

The Safety Board looks forward to reviewing the information being collected by EgyptAir and discussing these issues in proper cultural and airline perspective.

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OTHER ISSUES NOT IDENTIFIED IN FEBRUARY 7, 2000 LETTER

Evaluation of "control it" phrase

The Safety Board has requested the assistance of another US governmental agency in the examination of this phrase. Mr. Cash will report on the findings when available.

DFDR tape compatibility with EgyptAir equipment

In lieu of providing the DFDR tape to Teledyne, Safety Board staff have written software to write the DFDR data to a tape in a format compatible with EgyptAir read-out equipment. That tape will be provided to the EgyptAir delegation when completed.

Please let me know if you have any additional questions.

Sincerely,

[redacted]

Gregory Phillips
Investigator in Charge
for EgyptAir flight 990

cc: Dr. Bernard Loeb
Dr. Vernon Ellingstad

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National Transportation Safety Board
Washington, D.C. 20594

Attachment 3

April 28, 2000

Mohamed A. Hamid Hamdy
Engineer - General Manager Training
EgyptAir
Training Division
Cairo International Airport
Cairo, Egypt

Maher Ismaiel Mohamed
Head of Airworthiness - Central Administration
Egyptian Civil Aviation Authority
ECAA Complex 6th Floor
Cairo Airport Rd.
Cairo, Egypt

Dennis D. Chandler
Engineer - PW4000 Operability/ Propulsion System Analysis
Pratt & Whitney
400 Main Street M/S 162-15
East Hartford, CT 06108

John Hed
Flight Test Engineer
Federal Aviation Administration
Seattle Aircraft Certification Office, ANM-160S
1601 Lind Ave. S.W.
Renton, WA 98055-4056

Timothy Mazzitelli
Lead Engineer - Aerodynamics, Stability & Control
The Boeing Company
Building 10-16
535 Garden Ave. N.
Renton, WA 98055

Gentlemen:

I have completed Addendum 1 to the Aircraft Performance Study for the EgyptAir Flight 990 accident that discusses elevator blowdown angles and the possibility of aerodynamic causes for the elevator split recorded on the DFDR. The Addendum is enclosed for your review.

Please review the Addendum for factual accuracy and completeness, and forward your comments to me by Monday, May 8th. If you prefer, you can email your comments to me at [redacted]. After receiving and reviewing your comments I will update the Addendum as necessa[redacted] a final copy.

Thank you for your continued assistance in the investigation of this accident.

Sincerely,

[redacted]

John O'Callaghan
Senior Aerospace Engineer
Office of Research and Engineering

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NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Washington, D.C. 20594

April 28, 2000

Aircraft Performance - Addendum #1

Addendum to Group Chairman's Aircraft Performance Study
by John O'Callaghan

A. ACCIDENT

Location:	Sixty miles South of Nantucket, MA
Date:	October 31, 1999
Time:	0150 Eastern Standard Time (EST)
Flight:	EgyptAir Flight 990
Aircraft:	Boeing 767-366ER, Registration SU-GAP
NTSB#:	DCA00MA006

B. GROUP

Chairman: John O'Callaghan
Senior Aerospace Engineer
NTSB

Members: Mohamed A. Hamid Hamdy
Engineer - General Manager Training
EgyptAir

Maher Ismaiel Mohamed
Head of Airworthiness - Central Administration
Egyptian Civil Aviation Authority

Dennis D. Chandler
Engineer - PW4000 Operability/ Propulsion System Analysis
Pratt & Whitney

John Hed
Flight Test Engineer
Federal Aviation Administration

Timothy Mazzitelli
Lead Engineer - Aerodynamics, Stability & Control
The Boeing Company

C. SUMMARY

The Aircraft Performance Group Chairman's Aircraft Performance Study for the EgyptAir flight 990 accident describes the results of using the various data sources to define, as far as possible, the motion of EgyptAir Flight 990. The study introduces the aircraft motion data collected during the investigation, describes the methods used to extract additional aircraft motion information from Digital Flight Data Recorder (DFDR), radar, Cockpit Voice Recorder (CVR), and weather data, and presents the results of these calculations.

The DFDR data presented in the Performance Study indicates a split, or asymmetry, in the left and right elevator panels about 27 seconds after the initial movement of the elevators in the nose down direction that initiated the departure from cruise flight. This Addendum to the Performance Study examines whether or not the recorded elevator split could have been caused by differential hinge moments on the left and right elevator panels. The results of these calculations indicate that an aerodynamic cause for the split is inconsistent with the performance of the airplane and the data recorded on the DFDR.

This Addendum also presents the elevator deflection, throughout the flight profile described by the EgyptAir DFDR, that would result from a full nose-down elevator command under four different elevator control system conditions. These conditions are: (a) All three hydraulic systems operating; (b) Two of the hydraulic systems operating; (c) One of the hydraulic systems operating; and (d) All three hydraulic systems operating, but in a dual Power Control Actuator (PCA) valve jam scenario in which two of the PCAs are working to drive the elevator to its nose-down limit, but the third is working to keep it at neutral. For all of these conditions, the varying hinge moment on the elevators resulting from the changes in Mach number and angle of attack during the flight profile are accounted for. The results of the calculations are presented as plots of elevator deflection as a function of the Nantucket ASR-9 clock time presented in the Performance Study.

D. DETAILS OF THE INVESTIGATION

I. Hinge Moments Required to Produce Elevator Split

This section addresses the question of whether or not the elevator split recorded on the EgyptAir 990 DFDR could have been caused by aerodynamic forces on the tail surfaces. The flight condition chosen for this study is as follows:

Radar Time:	01:50:30 EST
Altitude:	18,800 ft.
Mach Number:	0.96
True Airspeed:	600 kts.
Dynamic Pressure:	670 lb/ft^2
Left Elevator:	4° Trailing Edge Up (TEU)
Right Elevator:	3° Trailing Edge Down (TED)

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To evaluate the aerodynamic loads on the tail surfaces required to result in the split, an assumption must be made about where the airplane's control system is attempting to position the elevators. At the flight condition under consideration, the elevator positions are split almost an equal amount about the faired elevator position, in opposite directions. These calculations therefore assume that the control system is attempting to command a 0° or faired elevator position.

With this assumption, the airloads on the right elevator must drive the elevator in the trailing edge down direction against the hydraulics, and those on the left elevator must drive the surface in the trailing edge up direction against the hydraulics. The airloads that tend to rotate the elevators about their hinges are expressed in terms of the elevator hinge moment coefficients, defined as

$$C_H = \text{Hinge Moment}/(q^*S^*c) \qquad [1]$$

where q = dynamic pressure, S = elevator reference area, and c = elevator chord. Documents provided by Boeing describe the C_H as a function of tail angle of attack, elevator deflection, Mach number, and flap setting. The tail angle of attack (α_H) is a function of the airplane body angle of attack, the downwash angle at the tail, and the horizontal stabilizer deflection. The Boeing documents also indicate the amount of hinge moment that can be balanced by the forces provided by the hydraulic actuators. In the problem under consideration, the elevator deflection, Mach number, dynamic pressure, and flap setting are defined by the flight condition. If there is asymmetric flow around the left and right elevators, then the α_H of the left and right elevators may be different, resulting in differential hinge moments and differing surface positions. The table below lists the angles of attack required on the left and right horizontal tail surfaces in order to overcome both the hydraulic actuators and the elevators' own tendency to return to a faired position, and drive the elevators to the split positions recorded by the DFDR at 01:50:30.

# of Hydraulic Systems Operating	α_H on left tail required to drive elevator 4° TEU	α_H on right tail required to drive elevator 3° TED	Angle of attack difference, left - right
0	10.3°	-5.5°	15.8°
1	18.2°	-11.5°	29.7°
2	26.2°	-17.5°	43.7°
3	34.2°	-23.5°	57.7°

Linearized equations at Mach 0.91 (the highest Mach number for which 767 C_H data is available) were used to derive the numbers shown in the table. These work well for small elevator deflections (+/-5°) and angles of attack. However, the equations break down at larger angles of attack, because they do not account for tail stall, and can give tail angles of attack well above the stall. According to Boeing data, at low speed the tail will stall (reach its maximum lift coefficient) at angles of attack of about +/- 21°. At high speed, the stall angles are probably somewhat smaller, though wind tunnel data does not exist for these conditions.

The table indicates that with hydraulic power equivalent to 2 or more hydraulic systems operating, there is no angle of attack below tail stall that will move the elevators to their split positions. The investigation has revealed that because the engine N2 values remained above 40% during the period for which DFDR data is available, no hydraulic power would have been lost in the time between when the engines were shut down and the DFDR ended.

Considering the cases for which the elevator split can be obtained with tail angles of attack below stall (corresponding to 0 and 1 hydraulic systems operating), note that a considerable angle of attack difference between the left and right horizontal tails is required. It is difficult to conceive of a flight condition that can generate such asymmetric flow about the left and right horizontals, but two possibilities are (1) a roll rate, and (2) a sideslip angle.

The half-span of the tail is approximately 30 ft. At 600 kts., to generate an 5° angle of attack change at the tip of one horizontal (i.e., a 10° difference between left and right horizontal tips) requires a roll rate of 170 degrees/second. At the flight condition in question the roll rate is approximately 2 degrees/second.

The dihedral angle of the tail is 7°. This angle will cause one horizontal to be at a different angle of attack than the other while in a sideslip. However, to change the tail angle of attack by 5° (difference of 10° between the tails) requires a sideslip angle of 35°. Such a sideslip angle is inconsistent with the lateral load factor, aileron angles, and rudder angles recorded on the DFDR, and at the flight condition in question is probably beyond the aerodynamic and structural capability of the airplane.

These calculations indicate that with little loss of hydraulic power, there is no angle of attack on the tails below the tail stall which can generate the elevator split recorded on the EgyptAir DFDR. Furthermore, even at reduced hydraulic power where angles of attack below tail stall can cause the split, the roll rates and sideslip angles required to generate the necessary asymmetric angles of attack on the left and right horizontal tails are inconsistent with the performance capabilities of the airplane and with the data recorded on the DFDR.

II. Elevator Blowdown Angles

The accident airplane departs cruise flight and enters a dive in response to the nose down elevator movements recorded on the DFDR. The Systems Group considered several failures in the elevator control system that could result in uncommanded nose down movement of the elevator surfaces (see the Systems Group Chairman's Factual Report for a discussion of these failures). One of the failures considered by the Systems Group involves the failure of two of the three elevator PCAs on one elevator surface, such that these PCAs act to move the elevator surface in the nose down direction, while the remaining PCA acts to keep the surface at its faired position. There are several different mechanisms for achieving this failure (see the Systems Group Factual Report for the details), but in each case the position of the failed surface results from the equilibrium between the two failed PCAs, the unfailed PCA, and the aerodynamic hinge moments. This section presents estimates of the

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position of the failed elevator surface throughout the dive recorded on the DFDR under a dual elevator PCA failure scenario.

When the elevator control system commands full nose down elevator, the amount of elevator deflection actually obtained (the "blowdown" position) is limited by the aerodynamic forces working to restore the elevator to its no load, or zero hinge moment, condition. The resulting elevator deflection is that which balances the aerodynamic hinge moment against the moment produced by the elevator PCAs. The hinge moment coefficient that can be balanced by the PCAs is given by

$$C_H = \frac{P_L A_P n l}{qSc} \qquad [2]$$

where P_L = PCA load pressure, A_P = PCA piston area, n = number of hydraulic systems operating, and l = PCA actuator moment arm. C_H is nondimensional; the dimensional hinge moment is given by Equation [1] in Section I.

The PCA load pressure P_L is nominally 2,950 psi, and so with three hydraulic systems operating (n = 3) the numerator of Equation [2] becomes $(2{,}950)A_P(3)l$. In the dual PCA failure scenario, two PCAs are acting to move the elevator nose down, while the third is acting to keep it at neutral. However, in this scenario, n in Equation [2] is not simply (2) - (1) = 1 as one might expect, because the unfailed PCA uses more hydraulic pressure to keep the surface at neutral than each failed PCA uses to deflect the surface nose down. As the unfailed PCA is overpowered by the failed PCAs, its power piston is backdriven by the elevator surface, and the hydraulic fluid that would normally drive the piston is driven out through a pressure relief valve. This valve is set to 3,600 psi, so the unfailed surface is essentially acting to keep the elevator at neutral with 3,600 psi pressure, while the failed PCAs are acting to drive the surface nose down with 2,950 psi pressure each. The resultant pressure moves the elevator surface down at (2)(2,950) - 3,600 = 2,300 psi. To determine the amount of hinge moment that can be balanced by this pressure, we can set P_L = 2,300 psi and n = 1 in Equation [2], or equivalently, keep P_L at 2,950 psi and set n = 2,300/2,950 = 0.78. This latter approach is used in the results shown below. The elevator blowdown curves are shown for four cases: three hydraulic systems operating normally (n=3); two systems operating normally and one system off (n=2); one system operating normally and two systems off (n=1); and the dual PCA failure scenario (n=0.78).

Equation [2] gives the hinge moment coefficient C_H that can be balanced by the elevator PCAs for various values of n. The elevator surface position that corresponds to this C_H is a function of Mach number (M) and angle of attack at the tail (α_H).

The best estimate of C_H is contained in the aerodynamic models of the Boeing 767-300ER engineering simulator. The simulator data is based on wind tunnel tests and updated with flight test data, where available. However, at high speed (flaps up), the simulator models C_H based solely on elevator deflection (δ_e), M, and stabilizer angle in "pilot units" (δ_{sPU}). While α_H is affected by δ_{sPU}, the simulator model of C_H at high speed does not include α_H explicitly (the low speed (flaps down) simulator model of C_H does include α_H explicitly). In order to account for the effect of changing airplane body angle of attack on the C_H and δ_e blowdown angles during the dive, an estimate of the effect of α_H on C_H at high speed must be obtained from the existing simulator models. The method used here to estimate this effect is described below.

The maximum Mach number contained in the simulator data is 0.91, corresponding to the dive speed limit of the airplane. During the accident, the maximum M attained during the time the DFDR was operating was 0.99. To estimate the C_H at Mach numbers above 0.91, Boeing extrapolated the 767 elevator hinge moment data to Mach 0.98 based on 777 wind tunnel data available at Mach numbers .91, .94, and .96. The 777 and 767 have aerodynamically similar horizontal tails and elevators. The extrapolated data describes C_H in a three dimensional table with δ_e, M, and δ_{sPU} as independent variables.

Because the simulator C_H data is dependent on δ_{sPU} and not α_H, the effect of changing the freestream body angle of attack (and also α_H) will not be reflected in the solution for δ_e using the data directly. To approximate the effect of changing α_H, we observe that:

$$\alpha_H = \alpha_B - \varepsilon + \delta_s \qquad [3]$$

where α_B is the body angle of attack, and ε is the downwash angle at the tail. ε is assumed to be approximately equal to the downwash angle at the wing:

$$\varepsilon \approx \frac{C_L}{\pi ARe} \qquad [4]$$

C_L is the lift coefficient, AR is the airplane aspect ratio, and e is a wing efficiency factor, assumed to be about 0.8.

The δ_s in Equation [3] is the angle the horizontal stabilizer chord makes with the fuselage reference angle, with positive angles in the leading edge up direction. This measure of stabilizer angle is different than the stabilizer angle recorded by the DFDR, which is in pilot units (δ_{sPU}). The relationship between δ_s and δ_{sPU} is

$$\delta_s = 2^\circ - \delta_{sPU} \qquad [5]$$

The C_H tables contain data for δ_{sPU} angles of 0° and 6°, corresponding to δ_s angles of 2° and -4°, respectively. The α_B associated with the table data corresponds to cruise flight conditions. If the δ_{sPU} angles in the tables could be replaced with equivalent α_H angles at cruise conditions, then the tables would describe the C_H as a function of α_H and could be used to estimate the effect of the changing α_B on the C_H throughout the dive.

From the DFDR data, while cruising at 33,000 feet, $\alpha_B = 3°$, $\varepsilon \approx 1.5°$, and $\delta_{sPU} = 3.2°$. Using Equation [5] gives $\delta_s = -1.2°$, and then $\alpha_H = 0.3°$ follows from Equation [4]. So at this condition, an α_H of 0.3° corresponds to a δ_s of -1.2°. If we hold α_B and ε constant, then a change in δ_s is equivalent to a change in α_H, and a δ_s of 2° would correspond to an α_H of

$0.3° + \{2° - (-1.2°)\} = 3.5°$. A δ_s of $-4°$ would correspond to an α_H of $0.3° + \{-4° - (-1.2°)\} = -2.5°$. By changing the C_H tables to be dependent on α_H instead of δ_{sPU}, and by associating the data corresponding to $\delta_{sPU} = 0°$ with $\alpha_H = 3.5°$ and the data corresponding to $\delta_{sPU} = 6°$ with $\alpha_H = -2.5°$, the C_H can be determined as a function of δ_e, M, and α_H.

To calculate the blowdown angle, the C_H that can be balanced by the PCAs is calculated using Equation [2]. At each point during the dive, M is known, and α_H can be calculated using Equations [3] and [4]. An initial estimate of δ_e is made and the corresponding C_H is determined from a three dimensional table lookup of the modified simulator tables using the δ_e estimate, M, and α_H as independent variables. This C_H is compared with the C_H from Equation [2], and if they do not match, the δ_e estimate is adjusted until they do. The resulting δ_e is the blowdown angle.

The solutions for δ_e with n = 0.78, 1, 2, and 3 are shown in Figure 1. These solutions are the blowdown angles corresponding to the Dual PCA Failure and various hydraulic systems turned off. The elevator positions recorded on the DFDR are also shown in Figure 1. The elevator blowdown angle is primarily dependent on the dynamic pressure, decreasing as dynamic pressure increases. Changes in angle of attack produce oscillations about the general trend set by the increasing dynamic pressure. Nonlinear Mach effects become more pronounced after about 01:50:07, where the Mach number is increasing through 0.86 and the slope of the blowdown curves changes abruptly. The extrapolated C_H data provided by Boeing indicates that the C_H for a given δ_e deflection starts to increase significantly above Mach 0.86, and at Mach 0.98 reaches over twice its Mach 0.8 value for some values of δ_e and α_H .

E. CONCLUSIONS

This Addendum to the Airplane Performance Study for the EgyptAir Flight 990 accident indicates that it is unlikely that the split between the left and right elevator surfaces recorded by the DFDR could have been produced by asymmetric aerodynamic forces acting on the elevator surfaces.

The Addendum also presents the elevator blowdown angles corresponding to different numbers of hydraulic systems powered on and off, and to a Dual Elevator PCA Failure scenario. The blowdown angles are estimated using extrapolated, non-linear elevator hinge moment data. The results of the calculations are shown in Figure 1.

[redacted]

John O'Callaghan
Senior Aerospace Engineer
April 19, 2000

EgyptAir 990 Elev[illegible] lowdown Angles
With Nonlinear Mach, Elevator Angle, and α_H Effects

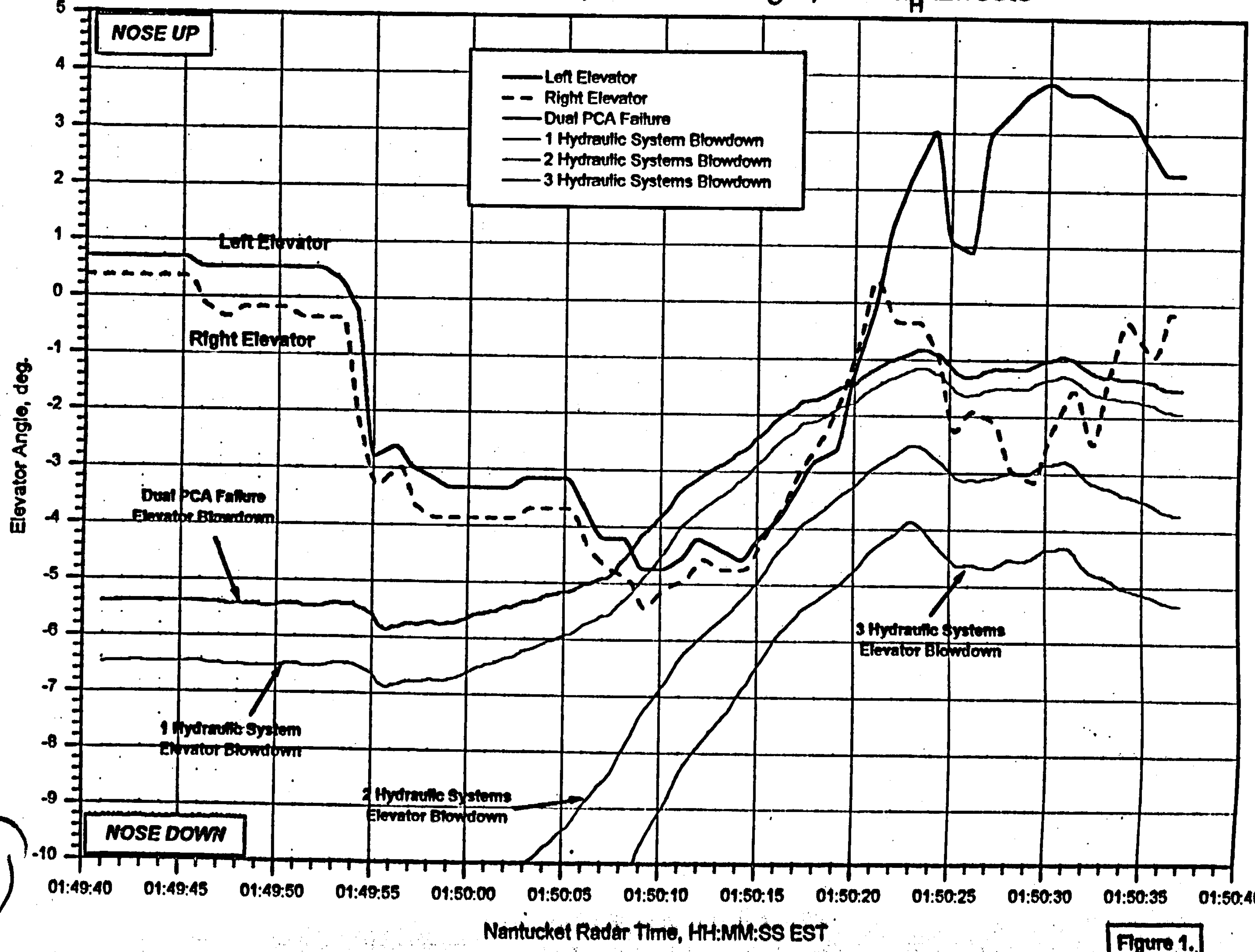

Figure 1.

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Attachment 4

May 2, 2000

John O'Callaghan
Senior Aerospace Engineer
Office of Research and Engineering

Subject: Addendum 1 to the Airplane Performance Study for the EgyptAir Flight 990 accident

Dear Mr. John

Kindly requested to:

A- Apply the same analysis on the Inboard and Outboard ailerons as they showed split behavior at the end of the dive similar to what was shown by the elevator, to validate the elevator analysis algorithm
B- Forward Boeing data containing the tail stall information

Thank you for your assistance

Sincerely,

[redacted]

Mohamed A. Hamdy
Engineer- General Manager Training
EgyptAir
Training Division
Cairo International Airport

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